Neutrino Factory Acceleration

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Acceleration Goals

- Start with beam after cooling
- Accelerate to energy at storage ring
  - 20–50 GeV, depending on physics
- Preserve beam emittance
  - Transverse beam size, angles
  - Longitudinal: energy spread, bunch length
- Avoid excessive muon decays
- Accelerate both muon signs

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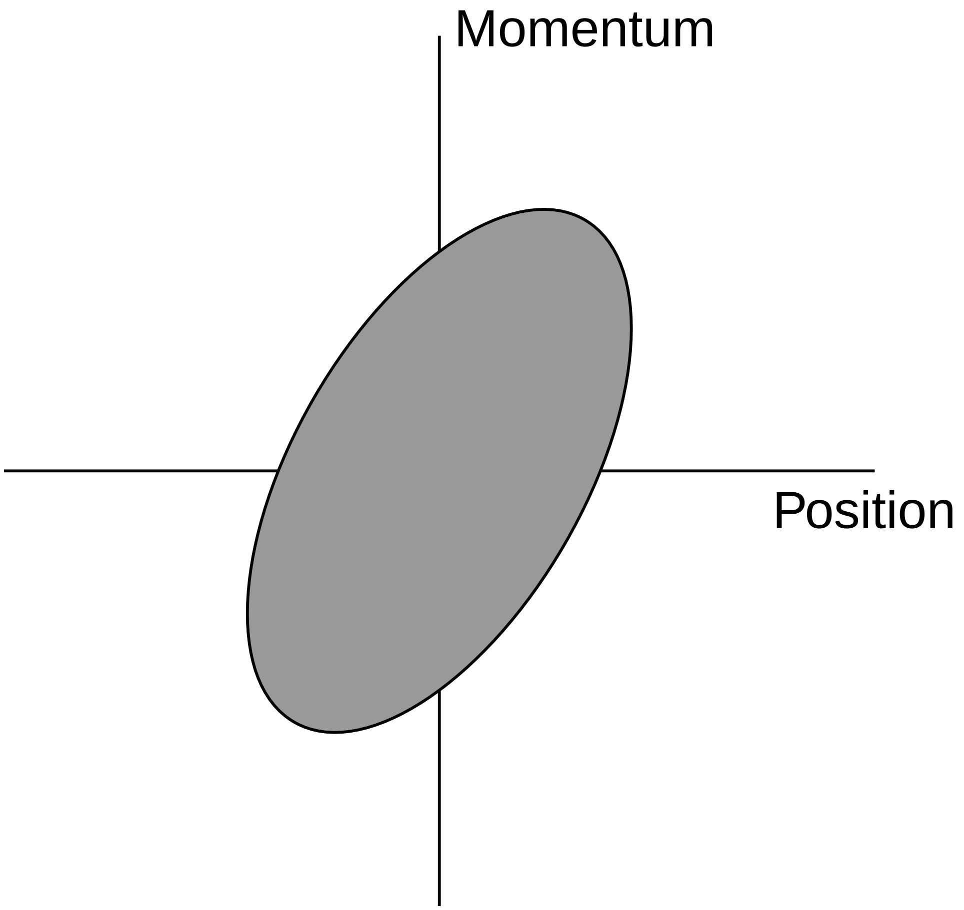
Typical Initial Beam Characteristics

- Kinetic energy around 120 MeV
- Normalized transverse acceptance: 30 mm
  - Varies with amount of cooling
- Normalized longitudinal acceptance: 150 mm
  - Number for 200 MHz system
  - Varies with RF frequency choice
- Both signs of muons
- Muons per sign per second: 2×10^{14} (4 MW)

Transverse Acceptance

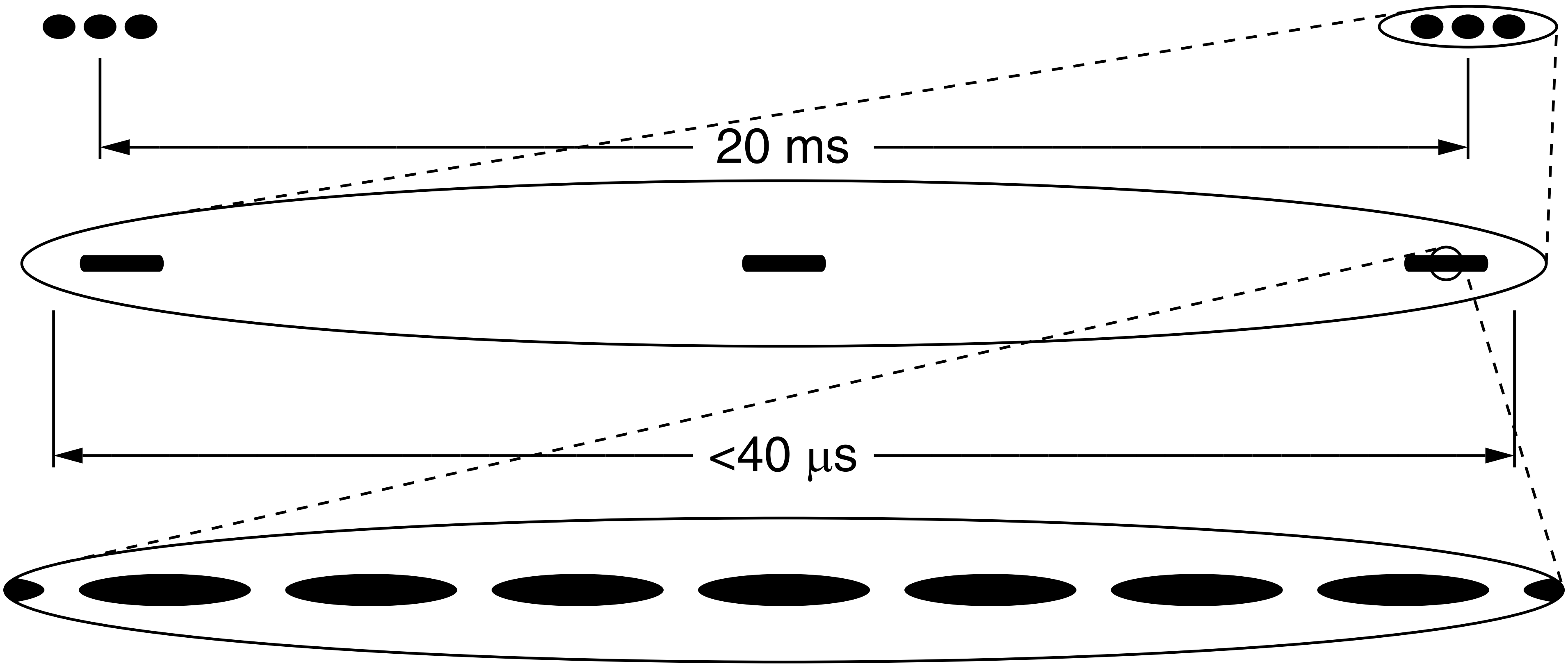
- Acceleration transmits all particles in ellipse
- Particles outside may be lost
- Normalized acceptance: area of ellipse divided by $mc\pi$



Incoming Bunch Train Characteristics

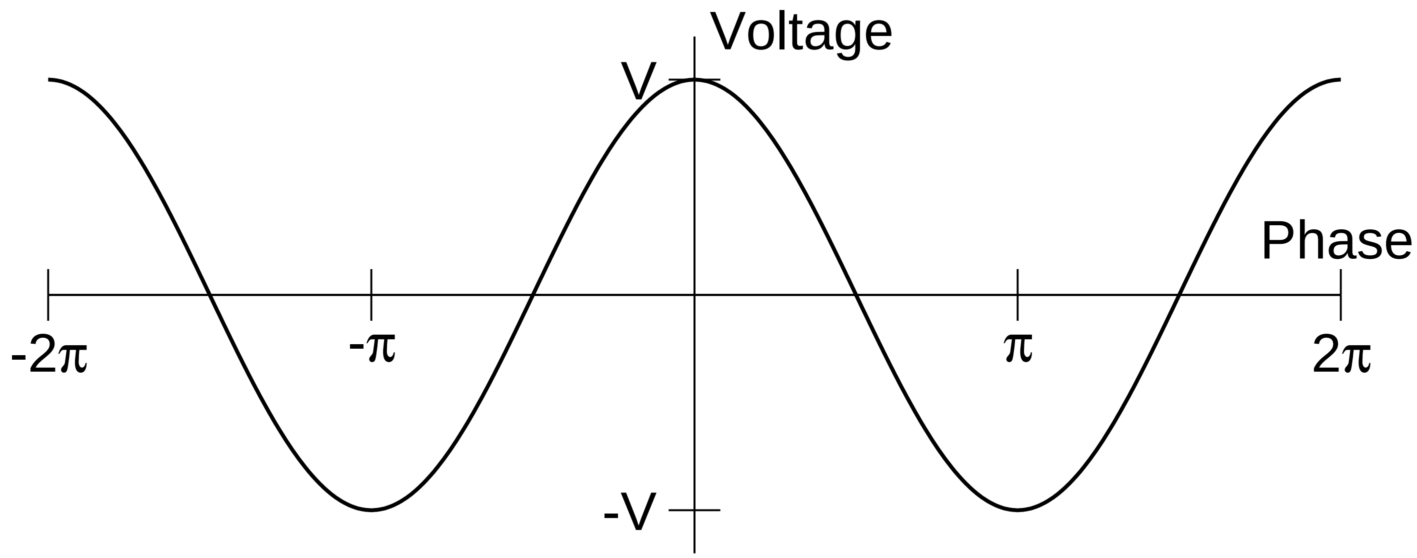
- 200 MHz system described
- 50 groups of 1 or more bunch trains per second
  - Proton driver, acceleration power use
- Bunch trains of 70–90 bunches
  - Bunch separation 5 ns (200 MHz period)
  - Only this changes when frequency changes
- All trains (1–5) in group occur within 40 μs or so
  - Target constraint

Incoming Bunch Train Characteristics



RF Cavity Basics

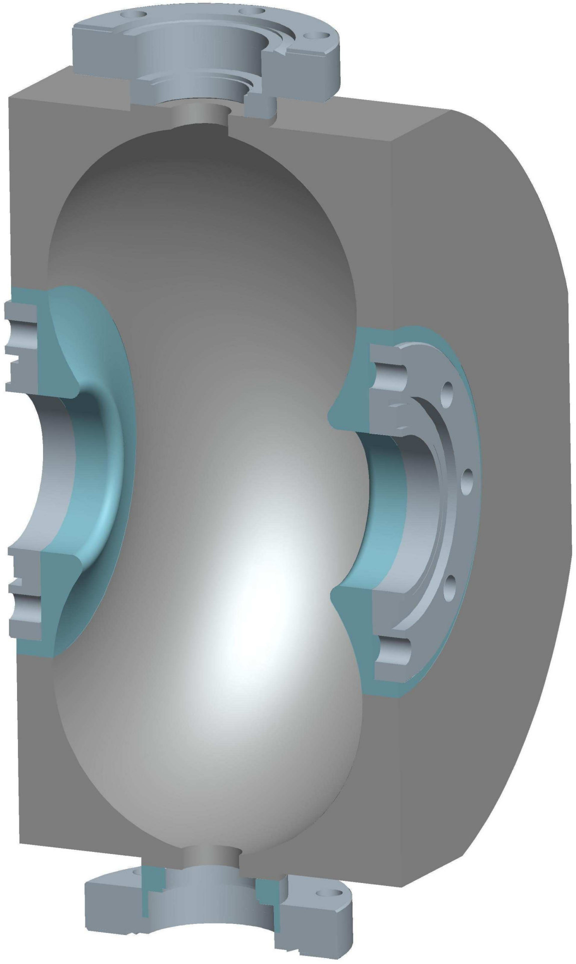
- RF cavity creates sinusoidally oscillating electric field, parallel to beam direction
- Depending on particle timing, increase or decrease energy by $\leqslant qV$



Cavity Stored Energy

- Standing wave in nearly closed cavity produces accelerating field
- Stored energy proportional to V^2

$$U = \frac{V^2}{\omega R/Q}$$



Power Delivery

- Power delivered to cavity
  - Increase stored energy
  - Counteract energy losses
- Cavity loses energy
  - Resistive losses into walls: $\propto V^2$
  - Power leaves the way it comes in: $\propto V^2$
  - Energy delivered to beam

$$\frac{dU}{dt} = P - \frac{V^2}{R} - IV = P - \frac{\omega U}{Q} - IV$$

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Power Delivery
Increase Stored Energy

- Constant power input: $U \to QP/\omega$
- Time scale to fill: Q/ω
- Width of cavity resonance: ω/Q
- Desire reduced power requirements
  - Reduce wall losses: superconducting
    - Bandwidth too narrow: cavity vibrations
    - Replace energy lost to beam anyhow
    - Allow more power in/out of coupler
  - Power through coupler limited

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Cavity Breakdown

- There is a maximum value for V
- Caused by local maximum for fields
  - Room temperature: max electric, near iris
  - Superconducting: max magnetic, outer part
- Ratio of local maximum to accelerating field
  - Depends on geometry: keep low
- Achieve highest breakdown V possible
  - Structures expensive (superconducting!)

RF Cavity Size

- Cavity size scales inversely with frequency
- 200 MHz cavities huge
- Can make smaller for given frequency

- Max field to accelerating voltage ratio higher
- Less accelerating voltage

RF System Requirements

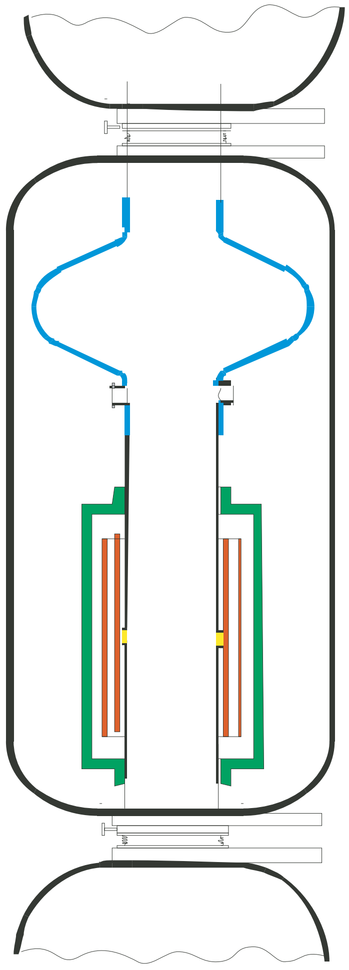
- Keep average accelerating field high: decays
- Keep RF power required low
- Sufficient transverse aperture for beam
- Sufficient longitudinal acceptance
- Use fewer cavities: cost

Linac

- Sequence of RF cavities in a straight line
- Interleaved magnets for transverse focusing
- Easiest, but most expensive option
  - RF systems are expensive
  - One pass through each cavity
- Longitudinal motion
  - Particles locked in time relative to each other
  - Exception: very beginning

Linac: Focusing

- Use solenoid focusing
- Low energies: solenoids stronger than quadrupoles
- Smaller beam sizes for given distance between magnets
  - Solenoid focuses in both planes



Linac: RF Frequency

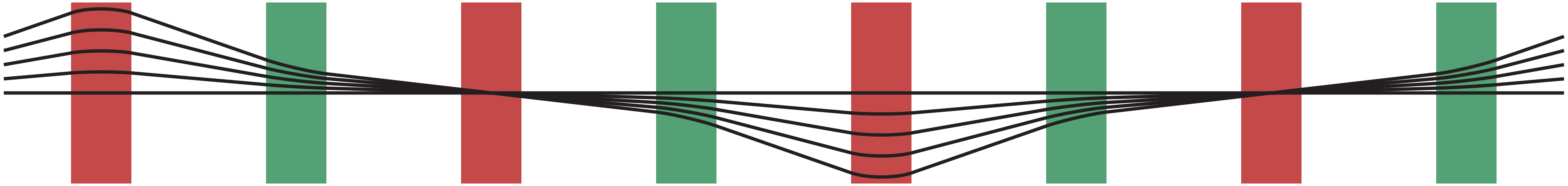
- 200 MHz bunches: any multiple of 200 MHz OK
- Forced to 200 MHz at beginning
  - Length of bunches
  - Aperture size
    - Beam size $\propto$ square root of cell length
    - Magnet fields increase with shorter cell length
    - Superconducting cavities: space between magnets and cavities

Linac: RF Frequency
Higher Energies

- Could increase RF frequency at higher energy
  - Benefits
    - Reduced power requirements
    - Easier to generate high powers
    - Lower cavity cost
  - Beam sizes smaller for given cell length
  - Difficult to reduce bunch length

Time of Flight Variation with Amplitude

- Particles with large transverse amplitudes arrive later
  - Angles particles make w.r.t. axis
- High ampltiude: lose synchronization with RF
- Limits amount of linac one can use
  - Length matters: reduced by higher gradient



Time of Flight Variation with Amplitude: Synchrotron Oscillations

- Cure: synchrotron oscillations
  - Accelerate on slope of RF
  - Fall behind: accelerated more, catch up
  - Arrive early: accelerated less, fall back
- Relativistic energies in linac
  - Velocity independent of energy
  - Must introduce bending
    - Path length depends on energy

Cavity Re-Use

- RF systems are the most expensive part
- Make multiple passes through cavities
  - Arcs that guide beam back through cavities
- Maximize passes through cavity to reduce cost

Beam Loading

- Beam extracts energy from cavity: $\Delta U = -QV$
- Multiple passes: more energy extracted
  - Energy not extracted is wasted
    - Problem with high rep rate
  - Introduces current dependence
- Different bunches in train see different voltages
- Higher frequency, effect stronger
  - Less stored energy

Beam Loading: Correction

- Add RF power
  - Bunch-to-bunch: impossible, time too short
  - Pass-to-pass ($\approx 1\ \mu$s): very high (12 MW)
- Thus, run on stored energy
  - Average power $\propto$ main pulse rep rate
- Synchrotron oscillations
- RF slightly off frequency
- Time dependence on energy, then RF

Ramping Synchrotron

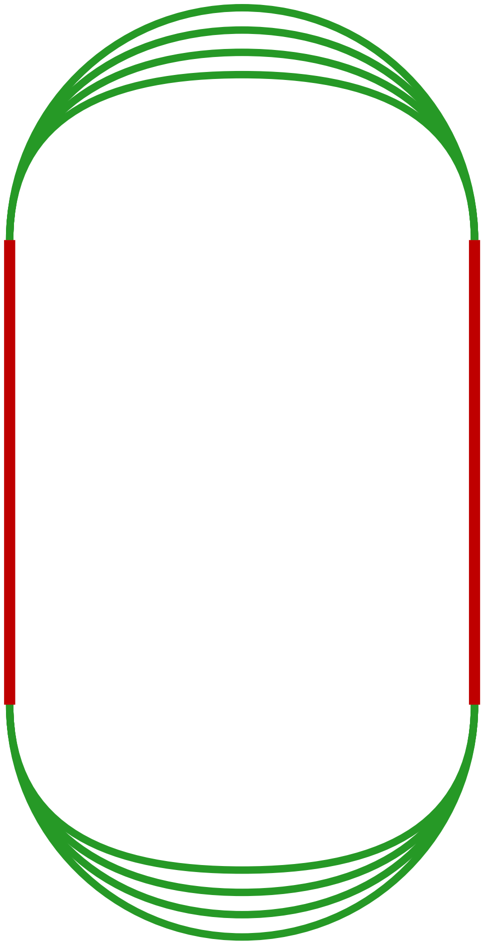
- Circular ring containing RF cavities
- Magnetic field proportional to beam momentum
  - Requires rapid variation of fields
    - Example: 4–20 GeV, average gradient 1.5 MV/m, 35 μs
- Problems with rapid field variation
  - Eddy currents (losses, undesirable fields)
    - Use thin magnet laminations
  - Power delivery

Ramping Synchrotron Power Delivery

- Example parameters
  - 500 m circumference, 4–20 GeV, 15 cm radius aperture
  - Max field $\geqslant$ 0.84 T
  - 10 MJ stored energy
  - 0.3 TW peak power to magnets
  - If energy lost: 500 MW average power!
    - Not this bad: most energy recovered

RLA

- Ramping magnets not practical
- Separate arc for each pass
  - Adjust arc length to keep RF synchronized
- Arcs make path length depend on energy
  - Synchrotron oscillations

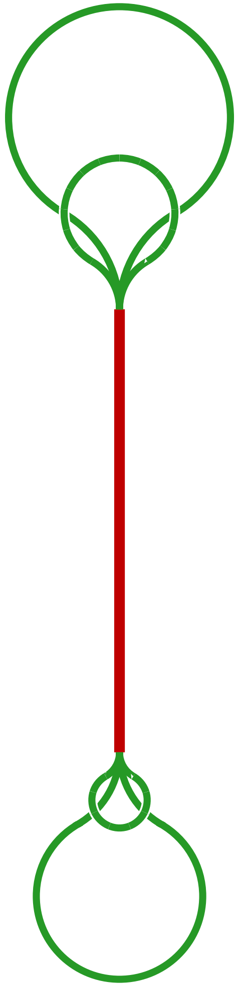


RLA: Switchyard

- Magnet separates beams into separate arcs
  - Based on energy
- Highest energy on one pass can’t overlap lowest on next
- Extra space for transverse size
- Extra space for coils
- Must maintain focusing: more than just dipole
- Practical limit: 4–5 passes

Dogbone RLA

- Change geometry to improve efficiency
- Use single linac, both directions
- Increase separation at switchyard, or
- Use less linac
- Arcs cross
    - Vertical bend, or
    - Low energy arc outside high energy
- Two bending directions complicates



RLA Design Considerations

- Each arc designed for single energy
  - At low energy, energy spread large (few %)
  - Requires nonlinear magnets
- Linac: many different energies
  - Use FODO lattice so it works at all energies
  - Velocity different on each pass
    - RF synchronization at low energy
    - Limits lowest energy

Fixed Field Alternating Gradient Accelerators (FFAGs)

- Make more passes through cavities
  - Eliminate switchyard
- Keep magnetic fields fixed
- All energies in same arc
  - This is the challenge
- Why not cyclotron?
  - Can’t do relativistic energies
- Bending and focusing in same magnets

FFAGs
Large Energy Range Accelerated

- Reason for difficulty: resonances
- Particles oscillate about closed orbit
- Frequency of oscillation depends on energy
- Integer of half integer number of oscillations: resonance
  - Particles move exponentially away from closed orbit
- n oscillations in m turns: nonlinear resonance

FFAGs: Time of Flight

- Time of flight depends on energy
  - Velocity variation with energy (small)
  - Path length variation with energy
- Must keep synchronized with RF
  - Vary RF frequncy
    - Rapid acceleration: can’t adjust RF phase
    - Would require large RF power
  - Limited number of turns
    - Get more turns with lower frequency

Scaling FFAG

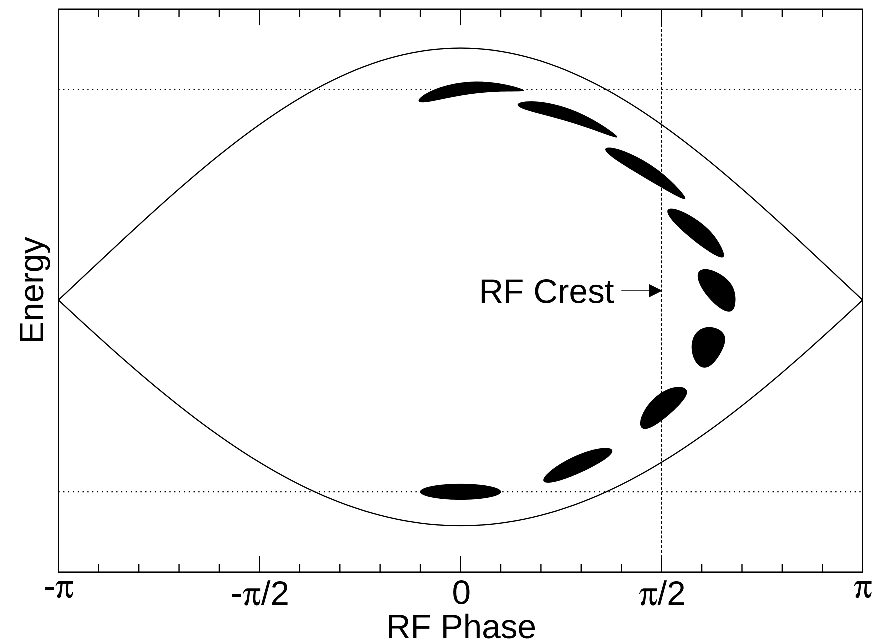
- Method to avoid resonance problem
  - Oscillation frequency independent of energy
- Know method to achieve this:
  $B_y(r,\theta,0) = B_0(\theta)(r/r_0)^k$
- Strong variation of time of flight with energy
- Magnet apertures
  - Superconducting at higher energies
  - Relatively large ($>$50 cm): expensive

Scaling FFAG Longitudinal Dynamics

- Time of flight varies monotonically with energy

$$\frac{\Delta T}{T} = \left(\frac{1}{k+1} - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p}$$

- Fixed RF frequency
- Half synchrotron oscillation
  - Synchronized to RF near central energy
  - Cross crest twice



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Scaling FFAG Longitudinal Dynamics

- Low frequency required
  - Low gradient
  - High power at low frequency
  - Few turns
- Not compatible with cooling
- NufactJ scheme
  - Use FFAGs starting with capture
  - RF frequencies 6.5–26 MHz

Scaling FFAGs
Harmonic Number Jump

- Different number of RF periods on each pass
  - Approximately same phase
- Allows high frequency RF
  - Won’t accelerate both muon signs
    - Ring filled with caviites
  - Problem making cavity wide enough
- Time not linear function of energy
  - Acceleration must depend on position

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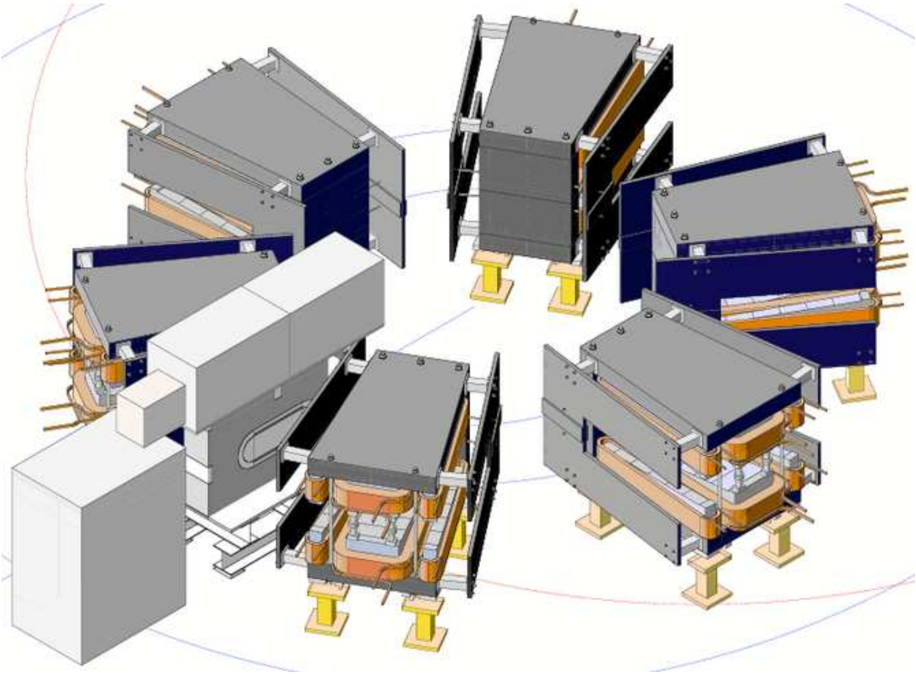
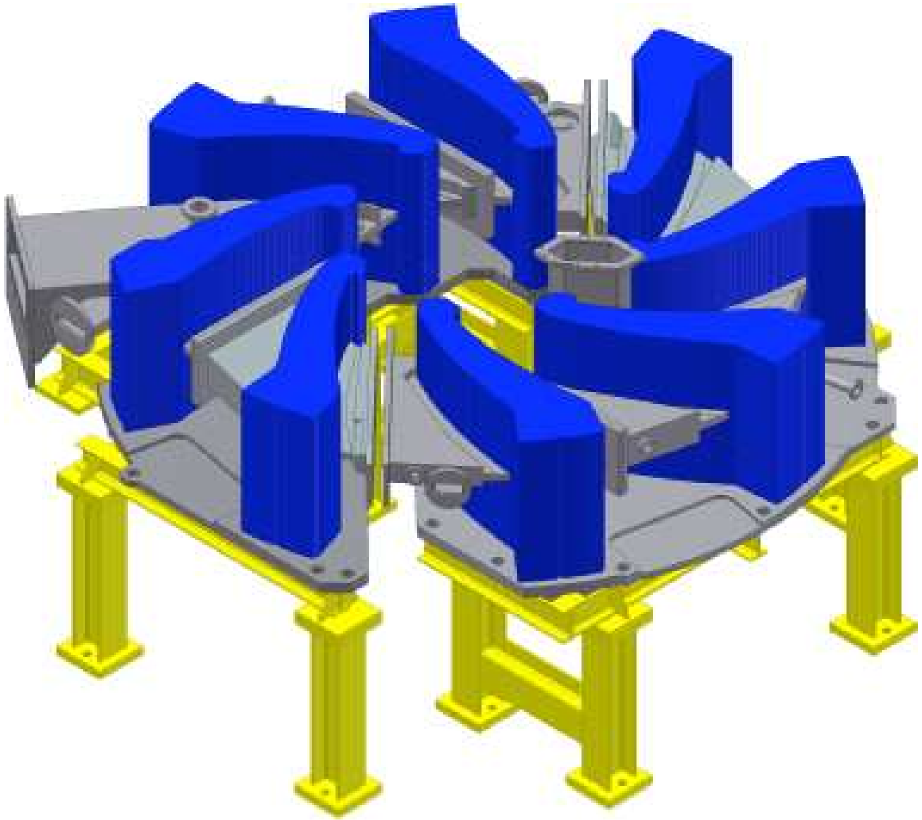
Scaling FFAGs Spiral Sector

- Magnets have a spiral angle
  - Edge angle gives focusing effect
- Potentially allows aperture reduction
- Used in many cyclotrons
- Complexity of making magnets
  - Especially for high fields

Radial vs. Spiral Sector





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Non-Scaling FFAG Motivation

- Why not scaling FFAG?
  - Large aperture superconducting magnets
  - Low frequency RF
- Non-scaling FFAG addresses these
  - Reduces magnet apertures
  - Allows high-frequency (200 MHz) RF

Non-Scaling FFAG
Basic Principles

- Must avoid resonance
  - Make every cell identical
    - Only need consider single cell
    - Errors still give weak resonances
    - Cyclotrons do this
  - Make magnets linear
    - Avoid nonlinear resonances
- Rapid acceleration
  - Pass through resonances quickly

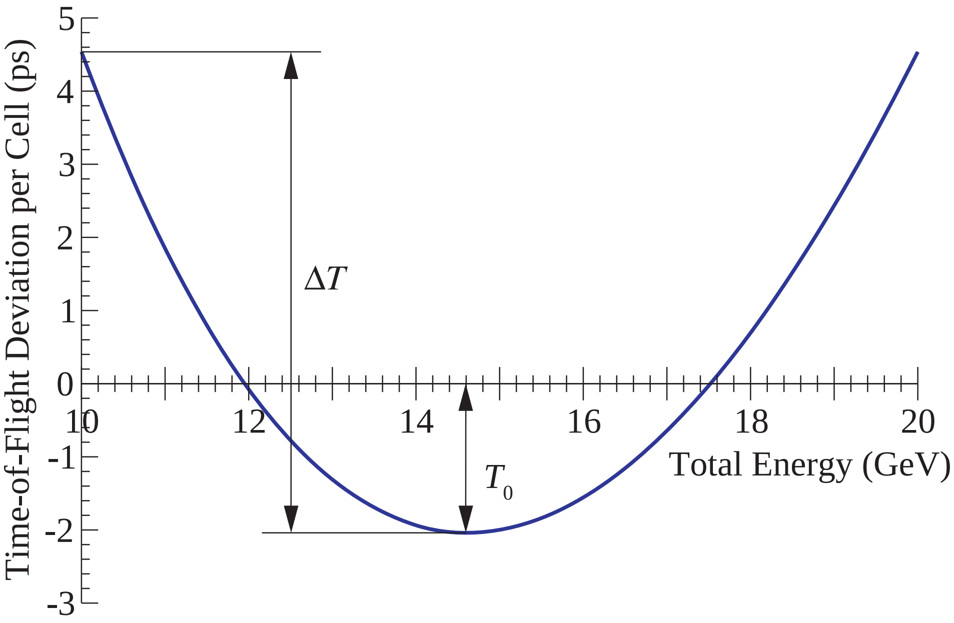
Non-Scaling FFAG Dispersion

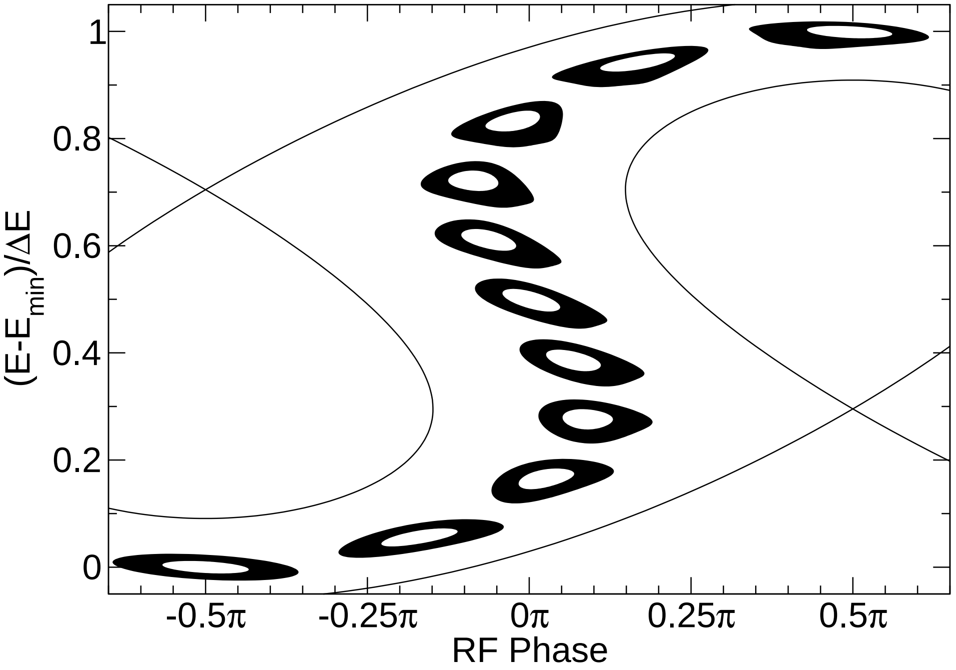
- Closed orbits vary with energy
  - Gives magnet aperture requirement
  - Determines time of flight variation
- Put bending in horizontally defocusing magnet
  - Less orbit variation with energy
  - Would require $k < -1$ in scaling FFAG
    - Never been done
    - Never been proven impossible...

Non-Scaling FFAG Longitudinal Dynamics

- Time of flight parabolic with energy
  - Minimizes time of flight range
  - Allows higher frequency RF
  - Possible due to small dispersion
- Synchronized to RF at two points
- Serpentine path in longitudinal phase space
  - Crosses crest three times
  - More time before going off-crest

Non-Scaling FFAG Longitudinal Dynamics





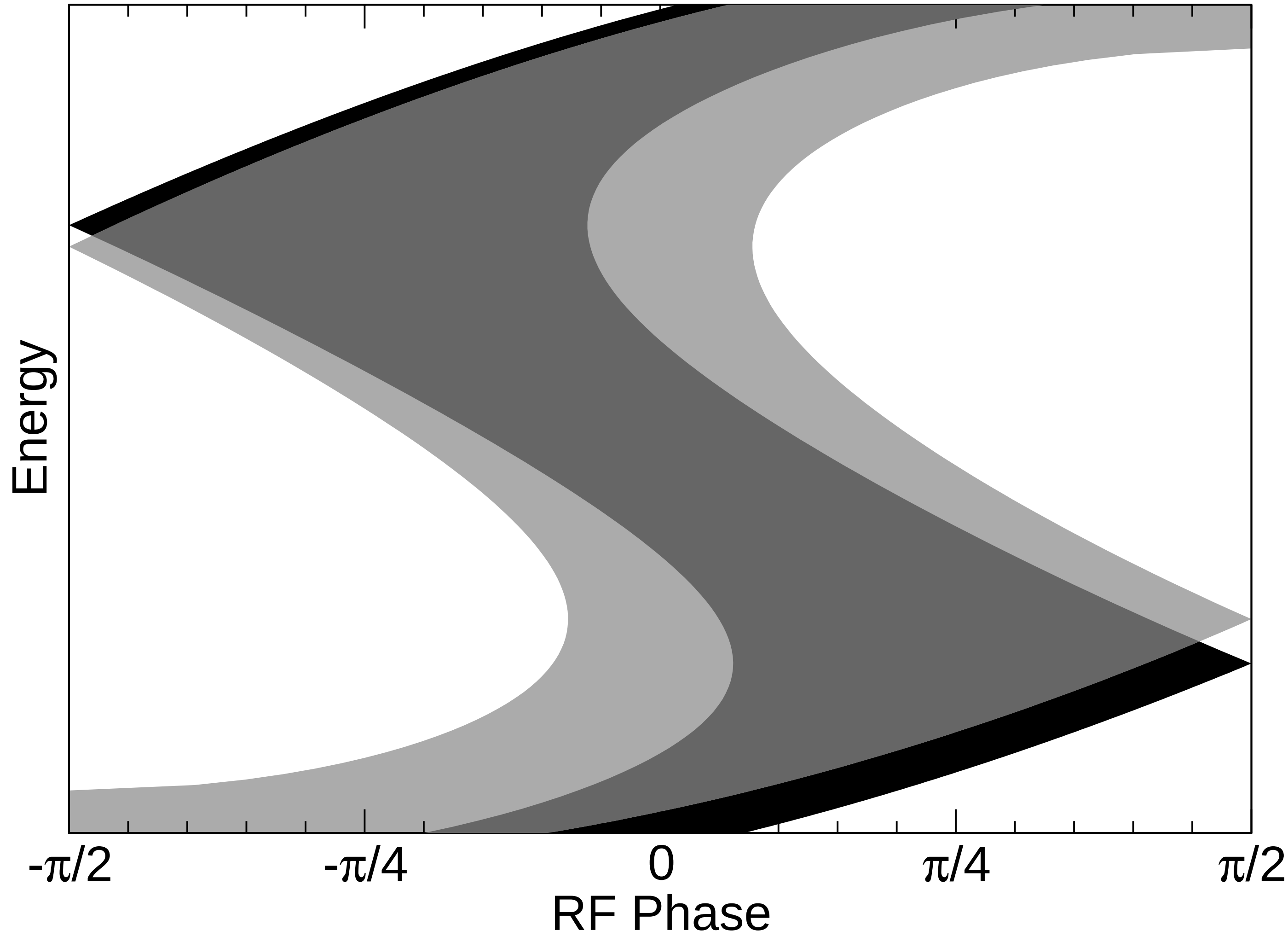
Non-Scaling FFAG Lattice Design

- Short cells important
  - Reduces aperture, time of flight variation
  - Need space for RF cavities
- Longer machine, smaller aperture
  - Bends reduced, dispersion reduced
- Maintain average accelerating gradient
  - Longer ring means fewer passes
- Makes low-energy FFAGs impractical

Non-Scaling FFAG
Time vs. Transverse Amplitude

- Time of flight depends on transverse amplitude
- Phase space different at different amplitudes
- High amplitude particle fall behind
- Makes many FFAG stages difficult
- Improvements
  - Higher gradient makes better
    - Makes FFAGs less efficient
  - Correct chromaticity: dynamic aperture

Non-Scaling FFAG
Time vs. Transverse Amplitude



Beam Loading

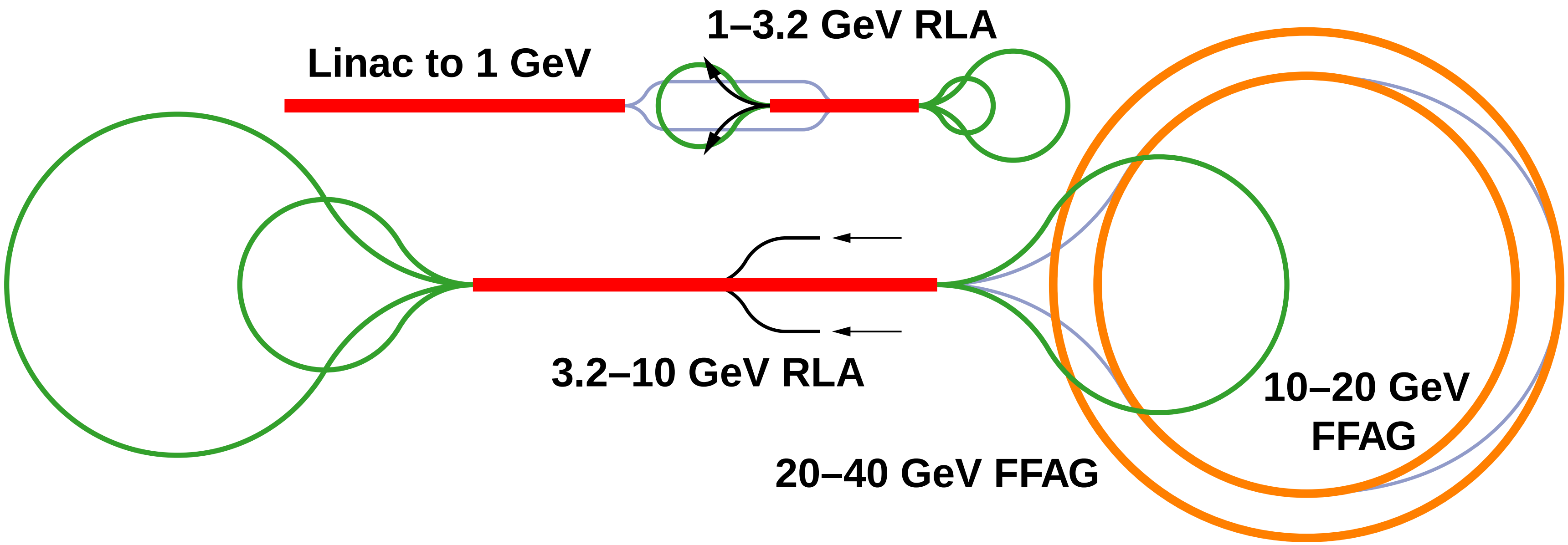
- Bunch trains within group
  - Separated by as little as 17 μs
- Each train extracts energy from cavities
  - More passes, more energy
- Each train should gain the same energy
  - Must replace energy extracted
  - 15 turns, 17 MV/m, 3 groups, 20 μs between: 4 MW!

Beam Loading
Addressing the Problem

- Input coupler can handle 1 MW. . .
- Don’t run multiple trains
- Run lower voltage
  - Makes decay, time of flight problem worse
- Different phase for each train (frequency offset)
- Create a better input coupler
- More time between trains
  - Target, proton driver may forbid

Overall Acceleration System

- First linac can't go too high
- Non-scaling FFAGs can't go too low
- RLA (dogbone?) in-between



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